Critical Modeling and Implementation Aspects for Seismic Incoherent SSI Analysis of Nuclear Structures with Surface and Embedded Foundations for Rock and Soil Sites

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Complementary to 2014 DOE NPH SSI Presentation

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Purpose of This Presentation:

To answer to the following important questions:

- What is the meaning of “incoherent motion”?
- How important is the foundation size influence on ISRS?
- How important is the seismic input directionality on ISRS?
- Is incoherency influencing the SSSI effects on ISRS, inter-building gap sizing, and computed soil pressures?
- How significant are incoherency effects on the o-p bending moments of foundation mats and walls?

The 2016 ACS SASSI NQA V3 software was used.

It can run 20-25 incoherent stochastic simulations in a single SSI run for all X, Y and Z directions. This is about 15-20 times faster than using the SSI restart for each simulation. What took 8 months for the APR1400 NI incoherent SSI project for only 8 incoherency modes using simple SRSS can take 8 days or less.
Coherent vs. Incoherent Wave Propagation Models

3D Rigid Body Soil Motion (Idealized)

1 D Wave Propagation Analytical Model (Coherent)
- Vertically Propagating S and P waves (1D)
  - No other waves types included
  - No heterogeneity random orientation and arrivals included
  - Results in a rigid body soil motion, even for large-size foundations

3D Random Wave Field Soil Motion (Realistic)

3D Wave Propagation Data-Based Model (Incoherent – Database-Driven Adjusted Coherent)
- Includes real field records information, including implicitly motion field heterogeneity, random arrivals of different wave types under random incident angles.

ANIMATIONS
The complex frequency response is computed as follows:

- **Coherent SSI response:**
  \[ U_s(\omega) = H_s(\omega) \ast H_g^c(\omega) \ast U_{g,0}(\omega) \]

- **Incoherent SSI response:**
  \[ U_s(\omega) = H_s(\omega) \ast S_g^i(\omega) \ast H_g^c(\omega) \ast U_{g,0}(\omega) \]

  \[ S_g(\omega) = [\Phi(\omega)][\lambda(\omega)]\{\eta_\theta\} \]

  - **Eigenmodes** of coherency kernel (deterministic part)
  - **Random phases** (stochastic part)

  Complex Fourier transform of control motion
  Coherent ground transfer function at interface nodes given control motion
  Incoherent ground transfer function given coherent ground motion and coherency model (random spatial variation in horizontal plane)
  Structural transfer function given input at interaction nodes

**Motion Incoherency Simulation in ACS SASSI**
Background on 2007 EPRI Validated Incoherent SSI Approaches Based on “Industry Consensus”

The 2007 EPRI validated approaches were based on industry consensus. The EPRI industry team uses three codes: ClassiInco, ACS SASSI, and SASSI Bechtel codes. The industry consensus was built around the SRSS approach that assumes zero phasing for SSI complex responses.

To match the team consensus results based on SRSS approaches, the Stochastic Simulation approach was used only with the “phase adjustment” option, that basically is zeroing the complex response phasing. The “theoretically exact” solution should include no phase adjustment.

It should be understood that by neglecting the complex random phasing, the incoherent SSI responses are less incoherent, and by this creates a bias toward coherent responses, that most likely is conservative for practical applications, but this is not always the case, as discussed herein.
How Many Modes Should Be Considered for SRSS Approaches? SS Considers All!

Low Frequency/Large Wavelengths/Only Few Low Order Incoherency Modes

High Frequency/Short Wavelengths/Low and High Order Incoherency Modes

Is the foundation sufficiently rigid to neglect high order modes at high frequency due to kinematic interaction effects?

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Comparative 20 vs. 40 Incoherent Mode Solution
Using SRSS Deterministic Approach

NI Complex Model - Rock Site
5% Damping SRSS (Approach 2) - CornerBottom
at Coordinates(-137.5, -87, 0) - Direction Y

NI Complex Model - Rock Site
5% Damping SRSS (Approach 2) - CornerBottom
at Coordinates(-137.5, -87, 0) - Direction Z

Transverse Direction

Vertical Direction

Basemat Corner ISRS of NI Complex with 50m Width
Is the 40 Modes SRSS Solution Convergent?

20 Incoherent Modes

40 Incoherent Modes

NI Complex Model - Rock Site
5% Damping SRSS (Approach 2) - CornerBottom at Coordinates(-137.5, -67, 0) - Direction Z

Why did not converge SRSS to stochastic simulation solution?

Basemat Corner Vertical ISRS of NI Complex with 50m Width
Motion Incoherency Differential Phasing Effects

Differential phasing produces time and space lags and through these, amplitude variations.

Kinematic SSI is important.
Differential Phasing Effects for Same Harmonic Inputs at Supports with Zero and Nonzero Time Lags

Symmetric Structure Subjected to Harmonic Inputs at Supports

Zero Differential Phase/Lag (Same Amplitudes)

Nonzero Differential Phase/Lag (Different Amplitudes)

( Inspired by Greg Mertz's 2014 DOE NPH example)
Effect of Zeroing Phases for Low-Mid Frequencies

For dominant single mode situations (in lower frequency range), the neglect of the (differential) phases that produce random amplitude variations in frequency space, basically changes the problem and departs from reality.

Zero-Phases Means No Differential Phasing

Nonzero-Phases Means Differential Phasing

Single Mode “Zero-Phase” Motion produces a “deterministic” motion closer to coherent

Single Mode “Non-Zero-Phase” Motion produces a realistic “random field” motion

Differential Amplitude Variations due to Differential Random Phasing

Mode 1 Contribution

<table>
<thead>
<tr>
<th>Freq</th>
<th>Part H</th>
<th>Part V</th>
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</thead>
<tbody>
<tr>
<td>1 Hz</td>
<td>100%</td>
<td>98.2%</td>
</tr>
<tr>
<td>8 Hz</td>
<td>84%</td>
<td>67%</td>
</tr>
<tr>
<td>25 Hz</td>
<td>7%</td>
<td>21%</td>
</tr>
</tbody>
</table>

At the lower frequencies, below 10 Hz, where a single mode (Mode 1) is governing, the zero-phase assumption practically neglects the differential phase variations between motion components due to incoherency.
Incoherency Simulation *With Zero-Phasing* (Loss of Physics)

Incoherency Simulation *With Random Phasing* (No Loss of Physics)

Only small wavelength component variations included!
Effects of Number of SSI Frequencies on Simulated Random Phasing

Records show significant Differential Phases (low-correlated) for closely-spaced SSI frequencies.

Typical SSI analysis interpolation filters Differential Phases (high-correlated) for closely-spaced SSI frequencies. We suggest use 200-300 SSI frequencies in the ACS SASSI manual.
Incoherent SSI Response Phasing Effects on
Large-Size RB Complex with 105m Width

Transverse Direction

Vertical Direction

Top of RVCC ISRS of NI Complex
Incoherent SSI Response Phasing Effects on Reduced-Size RB Complex with 50m Width
Incoherent SSI Response Phasing Effects on Reduced-Size RB Complex with 50m Width

High Elevation Center of NI Complex

Transverse Direction

Vertical Direction

High Elevation Center of NI Complex
Embedded SSI Models – Node Numbering Issue

SAME node numbering order for all levels

DIFFERENT node numbering order for all levels
Embedded SSI Models – Node Numbering Issue

SAME node numbering order for all levels

DIFFERENT node numbering order for all levels

Mode 9 at 11.72 Hz

REMARK: The sign of the mode shapes is random, + or -, depending on the node numbering.

Deterministic SRSS approach uses “arbitrary” criteria to maintain consistency between levels.
Mode 1 Sign Effect on Modal ATF & ISRS for X-Dir

Acceleration TF

Mode 1 Location 1

Mode 1 Location 2

Acceleration RS
Radial vs. Directional Coherency Models

Incoherency distance is

\[ D^2 = 2[(1-\alpha)Dx^2 + \alpha Dy^2] \]
Incoherent Motion Directionality Effects on ISRS for Large-Size RB Complex W/ Zeroing Phase

RBC (Rock, Phase Adjustment 1) -- ARS (Node 1389)  
Direction Y at Bottom E-Corner S

RBC (Rock, Phase Adjustment 1) -- ARS (Node 1389)  
Direction Z at Bottom E-Corner S

Transverse Direction

Vertical Direction

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2D Probabilistic Nonlinear Site Response (ACS SASSI OptionPRO & NON) for Site-Specific Coherency Models

1D Mean/BE Soil Profile Model
Generic Coherency Models, Statistical

2D Mean/BE Soil Profile Model
Site-Specific Coherency Models, Physics-Based
Developing *Site-Specific* Incoherency Models for NPP Area Using 2D/2V Probabilistic Soil Profiles (Vs, D)

Horizontal Mean Soil Layering (2D/2V Homogeneous Correlated Fields)

>>> Generic Coherency Models, Statistical, as Abrahamson, Luco, others

Slopped Mean Soil Layering (2D/2V Non-Homogeneous Correlated Fields)

>>> Site-Specific Coherency Models, Physics-based Modeling

After Vandeputte, France, 2016
Effects of Incoherency on Basemat Bending

Remark: Incoherent bending moments are 130%-240% of coherent bending moments.

Table 1: Basemat Bending Moments for A Soil Deposit with Vs = 3,300 ft/s

<table>
<thead>
<tr>
<th>Zone #</th>
<th>Coherent</th>
<th>Incoherent</th>
<th>Ratio Inc./Coh</th>
<th>Coherent</th>
<th>Incoherent</th>
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<td></td>
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<td>MXX</td>
<td>MXX</td>
<td>MYY</td>
<td>MYY</td>
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<tr>
<td>1</td>
<td>10.293</td>
<td>15.196</td>
<td>1.476</td>
<td>9.567</td>
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<td>8.386</td>
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<tr>
<td>5</td>
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<td>14.879</td>
<td>2.089</td>
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<tr>
<td>6</td>
<td>7.503</td>
<td>2.375</td>
<td>3.143</td>
<td>8.354</td>
<td>14.293</td>
<td>1.711</td>
</tr>
</tbody>
</table>
Incoherent vs. Coherent Seismic SSSI Effects

Generic NPP SSSI Model 1

(55,000 nodes with 5,000 int. nodes, 27,000 shells, 13000 solids, 11000 beams)

Soil Profiles

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RB Complex Coherent vs. Incoherent SSSI Effects on ISRS on Top of Internal Structure – Y and Z Directions

Rock Site

Soil Site

Horizontal

Vertical
RB Complex Coherent vs. Incoherent SSSI Effects on Bending Moments in Embedded Wall Near ABW Bldg.

Rock Site

Soil Site

Coherent
Mean of Incoherent

SSSI Model (RB: Side)
Moments for Shells (Rock Site) -- MXX

SSSI Model (RB: Side)
Moments for Shells (Soil Site) -- MXX

ANIMATIONS

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Conclusions for Investigated Cases

- Incoherent motion describes a realistic, 3D random wave field motion.

- For realistic, elastic foundations, truncating the number of incoherent modes could produce unconservative results in the high-frequency range.

- Zeroing the incoherent motion phasing usually produces overly conservative results in the mid-frequency range at the price of the loss of physics. Zero-phasing approaches not applicable to multiple time history analysis of RCL systems.

- Incoherent SSSI effects could be significant for soil sites by amplifying some SSI modes. Affect ISRS, soil pressures, foundation bending.

- Incoherent SSI responses require larger inter-building gaps, about 2 times.

- Incoherency motion directionality, radial vs. directional, produces less significant effects on SSI response.

- IMPORTANT: Improve incoherent SSI analysis by developing site-specific incoherency models.